REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	4/18/97	Final 4/1/92-12/31/96

4. TITLE AND SUBTITLE
Nonlinear Interaction in Ocean Surface Waves

5. FUNDING NUMBERS
N00014-92-J-1440 G

6. AUTHOR(S)
Stephen L. Elgar

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
School of Electrical Engineering and Computer Science
Washington State University
Pullman, WA 99164-2752

8. PERFORMING ORGANIZATION REPORT NUMBER
11F-3820-2773

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
n/a

a. DISTRIBUTION / AVAILABILITY STATEMENT
Unrestricted

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

12. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The immediate scientific objective of this project was to investigate the effects of nonlinearity in naturally occurring ocean surface gravity waves in intermediate and shallow water depths. Field observations of nonlinear effects on finite-depth waves were compared to model predictions and the changes in shapes of waves in the nearshore caused by near-resonant nonlinear wave-wave interactions were investigated.

Results from this study show that waves propagating over a shallow, flat beach undergo much stronger nonlinear evolution than observed in previous experiments on moderately sloping beaches. The observed nonlinear energy transfers to higher frequencies (frequency doubling) are well described by a Boussinesq model. Reflection of low energy swell and dissipation owing to wave breaking are predicted accuratetly by a model based on the nonlinear shallow water equations.

14. SUBJECT TERMS
nonlinear shoaling, spectral evolution, gravity waves, infragravity-frequency

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

Final Technical Report for the Project:
Nonlinear Interactions in Ocean Surface Waves, N00014-92-J-1440

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Results from this study show that waves propagating over a shallow, flat beach undergo much stronger nonlinear evolution than observed in previous experiments on moderately sloping beaches. The observed nonlinear energy transfers to higher frequencies (frequency doubling) are well described by a Boussinesq model. Reflection of low energy swell and dissipation owing to wave breaking are predicted accurately by a model based on the nonlinear shallow water equations.

The evolution of waves, currents, and bathymetry on a natural beach was observed during the Duck94 field experiment. In collaboration with R.T. Guza (Scripps Institution of Oceanography) a cross-shore transect of pressure gages, current meters, and sonar altimeters (to determine the seafloor location) was deployed near Duck, NC extending from the shoreline to about 8 m water depth. On monotonically and moderately sloping beaches, wave breaking limits the spatial extent over which nondissipative, nonlinear wave evolution can occur. However, for about 3 weeks during Duck94 the bathymetry included a nearly horizontal (flat), 2 m deep section extending about 80 m from the toe of the foreshore seaward to a small sand bar, resulting in significantly stronger nonlinear evolution than typically observed. The nonlinear evolution of waves propagating over this bathymetry was investigated in both the time and frequency domains, and the observed wave shapes and frequency spectra were compared to the prediction of 2 models. One model is based on the Boussinesq equations and the other on the shallow water equations. The shapes of the waves are described statistically by third moments (skewness and asymmetry) of the time series of sea-surface elevation. Skewness indicates the degree of peakedness of the waves (eg, the lack of symmetry about a horizontal plane caused by differences between the shapes of wave crests and troughs). Asymmetry indicates the degree of pitched-forwardness of the waves (eg, the lack of symmetry about a vertical plane caused by differences in the shapes of leading and trailing wave faces). A Gaussian sea surface has zero third moments.

The evolution of narrow band swell (significant wave height = 80 cm) undergoing frequency doubling (eg, a doubling of the number of waves) was studied. Near-resonant nonlinear quadratic interactions transfer energy from the swell (frequencies between $f =$ 0.08 and $f = 0.9$ Hz) to its harmonic ($0.16 < f < 0.18$) as the waves propagate across the nearshore. In 8 m depth the dominant wave period was about 11 s. In 2 m depth, at the seaward edge of the flat section, small crests began to emerge in the troughs of the

11 s swell. These resonantly excited waves continued to grow as the nonbreaking waves propagated over the 80 m wide flat section, resulting in twice as many wave crests on the foreshore. This frequency doubling is also evident in the evolution of the frequency spectrum of the wave field. At the foreshore the energy in the harmonic peak nearly equals that of the swell.

The observed wave evolution was compared to predictions of a model based on the nonlinear Boussinesq equations for unidirectional, nonbreaking waves propagating in shallow water. In this model quadratic, near-resonant interactions between pairs of swell components excite waves with the sum frequency (eg, twice the frequency of the swell). The Boussinesq model predicts accurately the observed third moments, especially the change in shape from pitched-forward waves at the seaward edge of the sand bar, to skewed, but symmetric about the vertical waves at the toe of the foreshore. The transfer of energy from the swell to higher frequencies is also well predicted by the Boussinesq model. The model-data comparisons indicate that the decrease in swell spectral level observed as the waves propagated across the flat beach section is owing primarily to nonlinear transfers.

The evolution of a more complicated wave field consisting of two low energy (the overall significant wave height is about 40 cm) swell peaks ($0.057 < f < 0.068$ Hz and $0.011 < f < 0.12$ Hz) was also investigated. In this case, the lower frequency swell partially reflects from the beach, resulting in large cross-shore modulations of energy from partial standing waves. Simultaneously, the low frequency swell interacts nonlinearly with the higher frequency swell, resulting in a transfer of energy to their sum frequency ($0.17 < f < 0.19$ Hz). The higher frequency swell dissipates owing to breaking as it propagates over the small sand bar. The nonlinear energy transfer is predicted accurately by the Boussinesq wave model. A model based on the shallow water equations predicts accurately the nodes and antinodes caused by the partial reflection of the low frequency swell and the breaking-induced decrease in energy of the higher-frequency swell.

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Steve Elgar and T.H.C. Herbers

93-P Elgar, S. and M.P. Kennedy, 1993 Bispectral analysis of Chua's circuit, J. Circuits, Systems, and Computing 3, 33-48.

93-P Elgar, S. and V. Chandran, 1993 Higher-order spectral analysis to detect nonlinear interactions in measured time series and an application to Chua's circuit, International Journal of Bifurcation and Chaos, 3, 19-34.

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PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
R&T Number: 321k003—05
Contract/Grant Number: N00014-92-J-1440
Principal Investigator: Steve Elgar and T.H.C. Herbers
Mailing Address: EECS 2752
Washington State University
Pullman, WA 99164-2752
Phone Number: 509 335-6602
E-mail: elgar@eecs.wsu.edu

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